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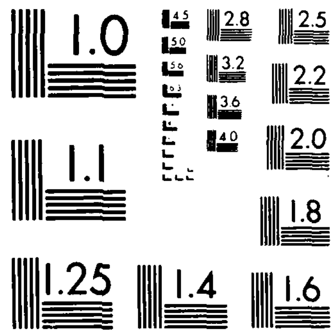

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The purpose of this work is to develop techniques to overcome the fundamental limits of present frequency standards---the second order and residual first-order Doppler shifts. ~~To this end~~ we study suitable frequency reference transitions in ions which are stored on electromagnetic traps and cooled by radiation pressure to < 1K.

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Summary of Work on

"COOLED ION FREQUENCY STANDARD"

(FY 87)

submitted to

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D.J. Wineland

Frequency & Time Standards Group

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Contract Description

The purpose of this work is to develop techniques to overcome the fundamental limits of present methods for high resolution spectroscopy and frequency standards--the second order and residual first-order Doppler shifts. To this end, we study suitable frequency reference transitions in ions which are stored in electromagnetic traps and cooled by radiation pressure to < 1K.

Scientific Problem

The scientific problems are (1) to suppress second order and residual first order Doppler shifts in atomic frequency standards in a fundamental way--by substantially reducing the kinetic energy of ions stored ion electro-magnetic traps, (2) to study suitable reference transitions in ions that can be used as frequency standards, and (3) to study the problems generic to all stored ion frequency standards. The goal is to achieve at least a factor of 100 improvement in accuracy over the present best device, the Cesium beam frequency standard, which has an accuracy of approximately 0.5 parts in 10^{13}.

Scientific and Technical Approach

Laser cooling is employed on all experiments in order to suppress Doppler shifts. Temperatures < 0.1K are routinely achieved. To avoid light shifts on "clock" transitions we investigate "sympathetic cooling" where one ion species is laser cooled and by Coulomb collisions cools another ion species of spectroscopic interest. We will continue experiments on Mg^+ and Be^+ in order to study generic problems with traps. We are developing a separate experiment for Hg^+ ions. These experiments have the goal of realizing a frequency standard with 10^{-15} or better accuracy.

PROGRESS DURING LAST CONTRACT PERIOD

*Summary of Progress since October, 1986

(1) "Quantum Jumps" Reported. Discrete fluorescence changes in a three level optical pumping scheme on a single ion have been observed and compared to theory. Seen in separate experiments on Hg^+ and Mg^+. (Figs. 3 and 6 below)

(2) Optical Mossbauer Effect of Single Ion. Have observed recoilless absorption and Doppler effect generated "phonon" sidebands of single trapped ion. Recoilless line has direct application for optical frequency standard. Cooling to theoretical laser cooling limit (1.7 mK) verified. (Fig. 7)

(3) Single Ion Absorption. The limit of absorption spectroscopy has been achieved by observing direct absorption on a single atomic particle.

(4) Quantum Jump Spectroscopy. Lifetimes and branching ratios of metastable Hg^+ ion measured by analyzing statistics of quantum jumps. Only noise in system is quantum noise of ion.

(5) Penning Trap/Superconducting Magnet System Made Operational. Trap has very high axial symmetry: initial tests are underway. Imaging phototube giving real time images of ion plasmas: speeds up measurements of plasma distributions by about two orders of magnitude.

(6) Static Properties of Ion Plasma. Several theoretical predictions about static properties of ion distribution functions verified - greatly simplifies measurements of velocity distributions (and second order Doppler frequency shift).

(7) Synchrotron Frequency Divider. Negative resistance magnetron compression theoretically investigated. Trap hardware nearly complete.

1. "Quantum Jumps". Our first observations of quantum jumps on Hg^+ were reported in Phys. Rev. Lett. 57, 1699 (1986). The canonical three level system addressed by many theorists was closely approximated by our single, trapped Hg^+ ion whose relevant energy levels are shown in Fig. 1.

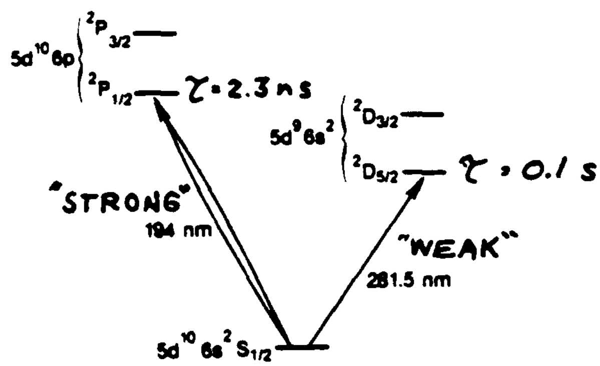

Fig. 1. Simplified optical energy-level diagram for HgII.

The basic idea for this experiment was initiated by Cook and Kimble (Phys. Rev. Lett. 54, 1023 (1985), and has been pursued theoretically in subsequent papers by Cook and Kimble and by other prominent quantum optics theorists including Cohen-Tannoudji, Dalibard, Loudon, Knight, Arecchi, Brewer, Javanainen, and others. Basically, in a three level system as shown in Fig. 2, two transitions in a single atom are

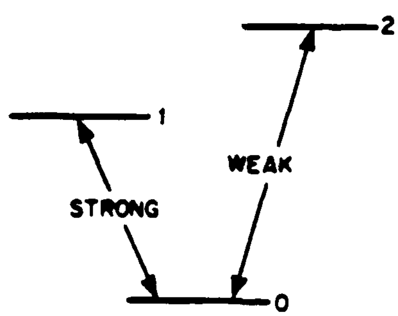

Fig. 2. Energy-level scheme for single atom double resonance experiments. (From Cook and Kimble, PRL 54, 1023 (1985)).

driven simultaneously. The lifetime of level 2 is assumed to be very long (eg; 0.1 s) while the lifetime of level 1 is assumed short (eg; few

ns). If the "weak" irradiation is turned off, then in practice one observes steady state fluorescence from the "strong" source (laser). (We assume for simplicity that were are not interested in the short time ($\lesssim$100 ns) statistics of the strong fluorescence although this can be included in the problem). If the weak irradiation is turned on, then the atom occasionally makes a transition to state 2 as signaled by a sudden decrease in fluorescence from the strong laser. The theoretical interest has largely concentrated on the statistics of this switching process. A simple quantum theory only predicts a steady decrease in the strong fluorescence. The "correct" theory must calculate photon correlation functions quantum mechanically.

The $^{198}Hg^+$ ion structure (Fig. 1) is essentially identical to that discussed by Cook, Kimble and others. In this case we make the state identifications "1" = $^2P_{1/2}$, "2" = $^2D_{5/2}$, "0" = $^2S_{1/2}$. The predicted fluorescence switching due to quantum jumps in and out of the $^2D_{5/2}$ level is shown in Fig. 3.

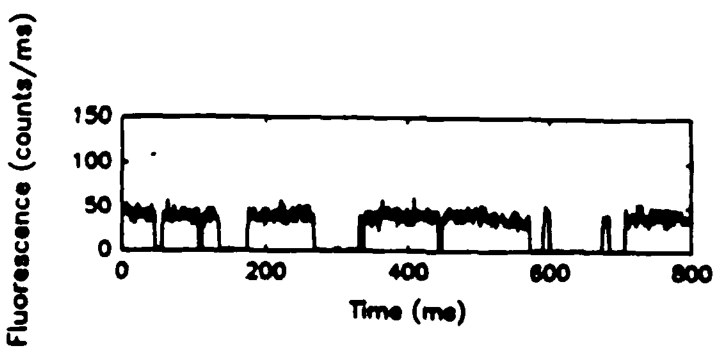

Fig. 3. 194 nm fluorescence switching caused by laser-induced quantum jumps of a single Hg^+ ion (Fig. 1) into and out of the $^2D_{5/2}$ level.

Other statistical properties can be derived from the quantum switching data. For example, each upward (downward) transition in the fluorescence can be assumed to mark the emission (absorption) of a $^2D_{5/2}$ - $^2S_{1/2}$ photon. Let $g_0(\tau)$ denote the probability that the (assumed) emission of a 281.5 nm photon is followed by the (assumed) emission of another 281.5 nm photon at a time τ later, normalized to 1 at τ=∞. For

our experimental conditions, theory predicts that $g_D(\tau)=1-\exp[-(R_+ + R_-)\tau]$, where R_+ and R_- are the transition rates to and from the fluorescence off condition, and this is in agreement with the data. In Fig. 4 we plot $g_D(\tau)$ from some of our quantum switching data. The fact that $g_D(\tau) \rightarrow 0$ at $\tau=0$ implies the existence of photon antibunching in the 281.5 nm radiation from the $^2D_{5/2}$ state. Because of the quantum amplification in the S-P scattering loop the photon antibunching is detected with nearly 100% efficiency.

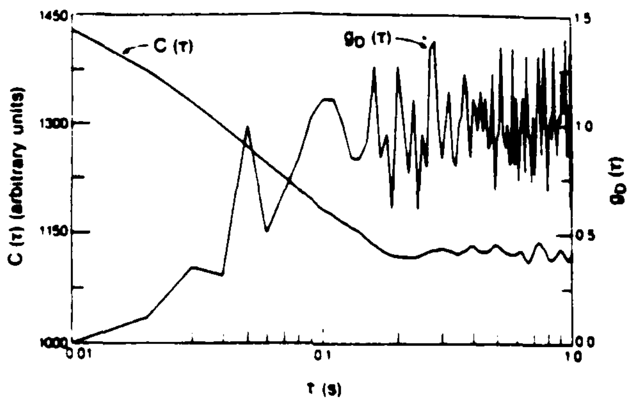

Fig. 4. Plots of the 194 nm fluorescence intensity correlation function $C(\tau)$ and the 281.5 nm emission correlation function $g_D(\tau)$. Photon antibunching in the 281.5-nm emission is inferred from the observation that $g_D(\tau) \rightarrow 0$ as $\tau \rightarrow 0$.

Quantum jumps have also been recently observed on a single $^{24}Mg^+$ ion in a Penning trap. This experiment differs from any previous experiments on quantum jumps in that (1) the jumps are governed entirely by spontaneous Raman transitions, (2) only a single laser is required (3) the ratio of fluorescence on to off times is independent of power and only weakly dependent on laser tuning. These features allow a quantative comparison with theory.

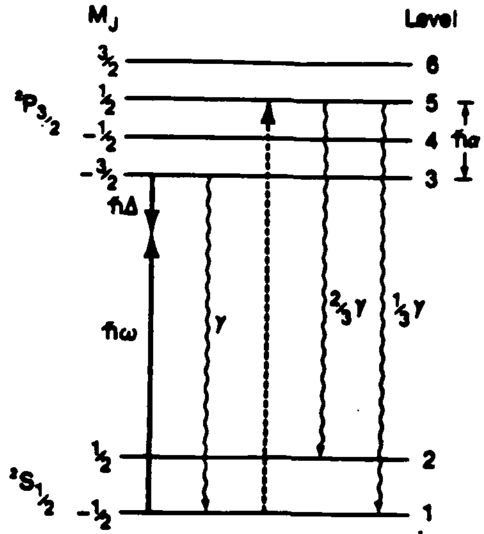

Fig. 5 The energy level structure of the $^2S_{\frac{1}{2}}$ and the $^2P_{3/2}$ states of an atom in a magnetic field. A laser of frequency ω is assumed to be tuned near the level 1 to level 3 transition frequency which gives rise to a (on resonance) Rabi frequency of Ω. The laser polarization is assumed to allow only $\Delta m_J = \mp 1$ transitions. The detuning from resonance is denoted by Δ. The total spontaneous decay rate of each excited level is γ and the energy separation between excited levels is given by $\hbar\alpha/2$. The dashed arrow indicates off-resonance excitation of the 1→5 transition by the laser. Off-resonance excitation of the 2→4 and 2→6 transitions are not shown in the figure. The wavy arrows denote the dipole allowed spontaneous decays from levels 3 and 5. It is assumed that $\alpha \gg \Delta, \gamma, \Omega$.

Fig. 5 schematically shows the Zeeman levels of the $^2S_{\frac{1}{2}}$ and $^2P_{3/2}$ states of $^{24}Mg^+$ in a magnetic field. It is assumed that the field is sufficiently weak that the levels are well described by the L-J coupling scheme. For convenience, the levels are labelled from 1 to 6, starting with the lowest ground level. The energy difference between levels i and j is denoted by $\hbar\omega_{ij} \equiv \hbar(\omega_i - \omega_j)$. A laser of frequency ω is assumed tuned near ω_{31}, the $^2S_{\frac{1}{2}}$, $m_J = -\frac{1}{2} \leftrightarrow {}^2P_{3/2}$, $m_J = -3/2$ (1⟷3) resonance frequency. If Δ denotes the detuning from resonance, then $\omega = \omega_{31} + \Delta$. $\hbar\Delta$

is assumed small compared to the energy separation of the upper states, which is assumed to be small compared to the $^2P_{3/2}$ and $^2S_{½}$ energy difference. The laser light is assumed to be linearly polarized with polarization perpendicular to the magnetic field axis. The only dipole decay allowed for level 3 is back to level 1. Therefore, the fluorescence from level 3 continues until an off resonance transition from level 1 to level 5 is induced and followed by a decay to level 2. There is a small probability of a non-resonant excitation to this level due to the finite linewidth of the transition. If level 5 becomes populated, the atom may decay to either ground state: back to level 1 (with 1/3 probability), where the $1 \leftrightarrow 3$ cycling resumes, or, to level 2 (with 2/3 probability), where the electron remains until another transition, again far from resonance, may remove it. The dipole selection rules allow transitions from level 2 to either level 4 or to level 6. Once in level 4, it may decay back to level 1 (with 2/3 probability) to resume the strong fluorescence cycling. The other Zeeman ground level, level 2, is the "shelf" level which removes the electron from the strongly fluorescing system. Thus, as in the three level "V" configuration, which utilizes two light sources, the fluorescence from this six level, one laser system is expected to alternate between periods of darkness and light. As opposed to other realizations of quantum jumps, the "shelf" level in this case "decays" via spontaneous Raman transitions since spontaneous radiative decay from level 2 to level 1 is negligible.

A sample of the resulting quantum jump data is shown in Fig. 6. One surprising feature of the data is that the ratio of on to off fluorescence time is equal to 16 even when the $1 \leftrightarrow 3$ transition is saturated. The source of this is discussed in the theory section below.

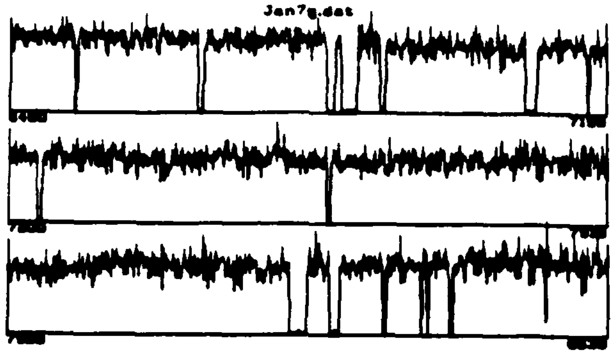

Fig. 6 Quantum jumps observed via the 280 nm fluorescence scattered from a single $^{24}Mg^+$ ion held in a Penning trap. The ratio of mean "on" to "off" times for the fluorescence is observed to be 16 independent of laser intensity.

2. <u>Recoilless absorption (Mossbauer effect) and optical Doppler sidebands on a single Hg^+ ion</u>. This is the first time this effect has been observed on a single trapped ion. In our experiments, a mercury atom that is ionized by a weak electron beam is captured in a miniature rf (Paul) trap that has internal dimensions of $r_0 \approx 455$ μm and $z_0 \approx 320$ μm. The rf trapping frequency was 21.07 MHz with a peak voltage amplitude of about 730 V. The ion is laser cooled by a few microwatts of cw laser radiation that is frequency tuned below the 6s $^2S_{1/2}$-6p$^2P_{1/2}$ first resonance line near 194 nm. When the Hg^+ ion is cold and the 194-nm radiation has sufficient intensity to saturate the strongly allowed S-P transition, 2×10^8 photons/s are scattered. With our collection efficiency, this corresponds to an observed peak count rate of about 10^5/s against a background of less than 50/s.

The 282-nm radiation that drives the $^2S_{1/2}$ - $^2D_{5/2}$ transition is obtained by frequency doubling the radiation from a cw ring dye laser that has been spectrally narrowed and stabilized in long term to less than 15 kHz. For this experiment, the dye laser is stabilized to a high-finesse optical cavity to give good short-term stability. In long term, the laser is stabilized by FM optical heterodyne spectroscopy to a

saturated-absorption hyperfine component in $^{129}I_2$. The pressure in the iodine cell was not controlled against temperature variations, and this gave rise to pressure induced frequency fluctuations that dominated the stability of the laser for times greater than about 10 s. The frequency of the laser is scanned by tuning the frequency applied to an acousto-optic modulator through which the laser beam is passed. We eliminated angle variation in the beam that was frequency-shifted and scanned by using the twice-frequency-shifted beam obtained by retroreflecting the first-order frequency-shifted beam back through the crystal. A computer controls the frequency and amplitude of the synthesizer that drives the acousto-optic modulator. Up to a few microwatts of 282-nm radiation could be focused onto the ion in a direction either orthogonal to, or counter-propagating with the 194-nm light beam. A magnetic field of approximately 1.2 mT (12 G) was applied parallel to the electric field vector of the linearly polarized 282-nm radiation to give well resolved Zeeman components. This configuration gives a selection rule of $|\Delta m_J|$ = 1 for the electric-quadrupole-allowed transitions to the various Zeeman states.

Optical-optical double resonance utilizing quantum amplification was used to detect transitions driven by the 282-nm laser to the metastable $^2D_{5/2}$ state. Our version of this method makes use of the fact that the 194-nm fluorescence intensity level is bistable; high when the ion is cycling between the S and P states (the "on" state) and nearly zero when it is in a metastable D state (the "off" state). The fluorescence intensity in the "on" state is high enough that the state of the atom can be determined in a few milliseconds with nearly 100% efficiency. The full measurement cycle was as follows: A series of measurements of the 194-nm fluorescence was made, using a counter with a 10-ms integration period. As soon as the counter reading per measurement period was high enough to indicate that the ion was in the "on" state, the 194-nm radiation was shut off and the 282-nm radiation was pulsed on for 20 ms. Then, the 194-nm radiation was turned on again, and the counter was read. If the reading was low enough to indicate that the ion had made a transition to the $^2D_{5/2}$ state (the "off" state), the signal was defined

to be 0. Otherwise, it was defined to be 1. The 282-nm laser frequency was then stepped, and the cycle was repeated. As the laser frequency is swept back and forth through the resonance, the quantized measurement of the fluorescence signal at each frequency step is averaged with the previous measurements made at that same frequency. Since we could detect the state of the ion with nearly 100% efficiency, there was essentially no instrumental noise in the measurement process. Occasionally, while the 194-nm radiation was on, the ion decayed from the $^2P_{½}$ state to the metastable $^2D_{3/2}$ state rather than directly to the ground state. This process led to a background rate of false transitions which was minimized by the quantized data-collecting method described above and by decreasing the 194-nm fluorescence level (thereby decreasing the $^2P_{½}$ - $^2P_{3/2}$ decay rate) until it was just high enough for the quantized detection method to work. The quantized measurement scheme also removes any contribution to the signal baseline due to intensity variations in the 194-nm source. The 282-nm and 194-nm radiation were chopped so that they were never on at the same time. This eliminated shifts and broadening of the narrow 282-nm resonance due to the 194-nm radiation.

Figure 7 shows the fluorescence signal obtained from an 8 MHz scan of the 282 nm laser through the $5d^{10}\ 6s\ ^2S_{½}$ (m_J = -½) → $5d^9\ 6s^2\ ^2D_{5/2}$ (m_J = ½) Zeeman component of the laser-cooled Hg^+ ion. The recoilless absorption resonance (carrier) and the motional sidebands due to the secular motion of the ion in the harmonic well of the rf trap are completely resolved. The inhomogeneous rf electric field produces a pseudopotential harmonic well with a radial frequency of approximately 1.46 MHz and an axial frequency of approximately twice the radial frequency, or about 2.9 MHz. An ion trapped in this pseudopotential well will execute nearly independent harmonic motions in the radial and axial directions. These harmonic motions frequency modulate the laser radiation as seen by the trapped ion and produce sidebands on the carrier frequency at the radial and axial frequencies and their harmonics. Thus, the number and amplitude of sidebands is a direct measure of the amplitude of the ion's motion and its effective temperature. In Fig. 7, only two pairs of sidebands are obtained. In this figure the 282-nm

intensity is adjusted to be close to saturation on the carrier in order to enhance the relative strength of the sidebands to the carrier. Also, the laser linewidth was broadened to about 80 kHz (at 563 nm) by modulating the frequency of the acousto-optic modulator in order to reduce the number of data points required for the sweep. In subsequent traces, a careful comparison of the sideband intensities, including the effects of saturation, gives an ion temperature for the secular motion of about 1.6 mK. This is near the theoretical laser cooling limit for $^{198}Hg^+$ on the first resonance line at 194-nm given by $T_{min} = \hbar\gamma/2k_B \approx 1.7$ mK.

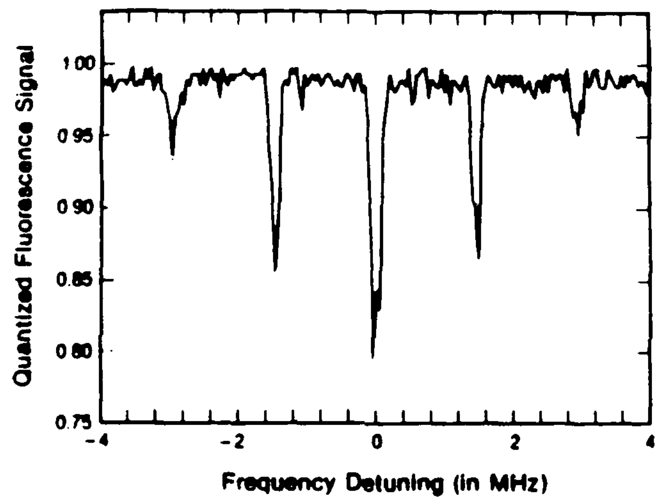

Fig. 7 Quantized signal showing the electric-quadrupole-allowed $5d^{10}$ 6s $^2S_{1/2}(m_J = -1/2)$ - $5d^9$ $6s^2$ $^2D_{5/2}$ $(m_J = 1/2)$ transition in a single, laser-cooled $^{198}Hg^+$ ion. On the horizontal axis is plotted the relative detuning from line center in frequency units at 282 nm. On the vertical axis is plotted the probability that the fluorescence from the 6s $^2S_{1/2}$ - 6p $^2P_{1/2}$ first resonance transition, excited by laser radiation at 194 nm, is on. (See Fig. 1) The electric-quadrupole-allowed S-D transition and the first-resonance S-P transition are probed sequentially in order to avoid light shifts and broadening of the narrow S-D transition. Clearly resolved are the recoilless absorption resonance (carrier) and the Doppler sidebands due to the residual secular motion of the laser cooled ion. The integration time per point is about 16 s (230 measurement cycles).

The narrowest linewidths obtained on the "carrier" in Fig. 7 are about 30 kHz (at 1.07×10^{15} Hz). This linewidth was dominated by laser linewidth. The radiative linewidth is only 1.6 Hz and the goal is now to narrowband the laser to about 1 Hz or less in order to achieve an accurate optical frequency standard.

3. Single Ion Direct Absorption. We have for the first time observed direct absorption of a single atom where absorption is detected as a decrease in the radiation transmitted through the absorber. This might be regarded as the detection limit of simple absorption spectroscopy since we are at the single atom level.

Our experimental configuration is shown in Fig. 8. Since we are interested in the case where $N \approx 1$, a single, laser-cooled $^{198}Hg^+$ ion was confined in a miniature rf trap with inside endcap-to-endcap spacing $2z_0 = 0.064$ cm and inner ring diameter $2r_0 = 0.091$ cm. With a ring-to-endcap voltage $V_T \approx (10 + 400 \cos \Omega t)V$, where $\Omega/2\pi = 21.07$ MHz, the ion was confined to a space with linear dimensions < 0.25 μm. A narrowband (width < 5 MHz) radiation source at 194 nm ($P \approx 3$ μW) was tuned near the 6s $^2S_{1/2} \rightarrow$ 6p $^2P_{1/2}$ first resonance transition in $^{198}Hg^+$ and focused through the trap and onto the ion. This radiation source was derived from sum-frequency mixing a dye laser (790 nm) and a frequency doubled Ar^+ laser (257 nm). The detector was a vacuum photodiode with a Cs-Te photocathode. In order to suppress amplitude noise from the 194 nm source, it is desirable to modulate the absorption at a high frequency. This was accomplished by applying a voltage, V_m, to one trap endcap. This displaced the ion from its equilibrium position in the rf trap and caused its velocity, which has a component along the direction of the 194 nm beam, to be modulated at the trap rf frequency Ω. That is, the static electric force was compensated by the pseudopotential force which gave rise to ion micromotion at frequency Ω. Due to the first-order Doppler shift, the resonance frequency of the ion was modulated at Ω. As indicated in Fig. 8, the modulated-absorption signal current was detected by a tuned circuit whose equivalent parallel resistance, was $R_D \approx 300$ kΩ

Unfortunately, the detector also picked up radiation from the unshielded trap electrodes, which gave a false signal which was unstable. To avoid this problem, we switched the phase of the absorption signal by 180° by switching the sign of the voltage V_m applied to the endcap at the frequency $\omega/2\pi$ = 2kHz. Therefore, after the first mixer (M1), the absorption signal appeared at frequency ω which we then converted to a dc voltage in M2. To avoid drifts at the output of M2, we switched the phase, $\phi_{\omega 1}$, of V_m by 180° every second and used a voltage-to-frequency converter (V/F) followed by an up/down counter to display the signal. The values of V_m, and the phases ϕ_Ω and $\phi_{\omega 2}$ were adjusted to give maximum absorption signal. The simultaneously recorded absorption and fluorescence signals are shown in Fig. 9.

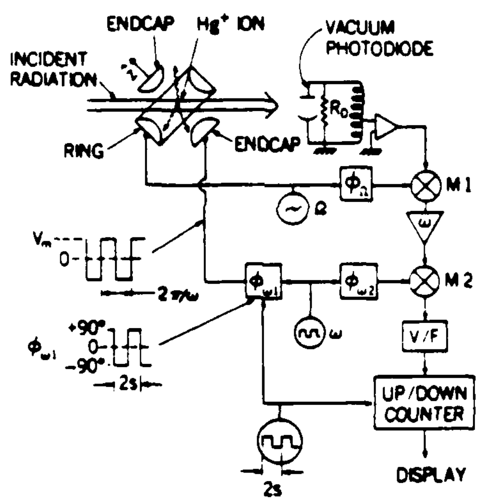

Fig. 8 Schematic diagram of the apparatus. Absorption from a single $^{198}Hg^+$ ion is detected as a change in current in the vacuum photodiode. This absorption is modulated at frequency Ω by applying a voltage V_m to one endcap electrode of the trap. To avoid a false signal from stray radiation picked up by the detector, the sign of V_m is alternated at frequency ω. To avoid drifts at the output of mixer M2, a third modulation at 0.5 Hz of the phase of ω and the sign of the signal at M2 is converted to dc by the up/down counter. V_m, ϕ_Ω, and $\phi_{\omega 2}$ are adjusted to maximize the display output.

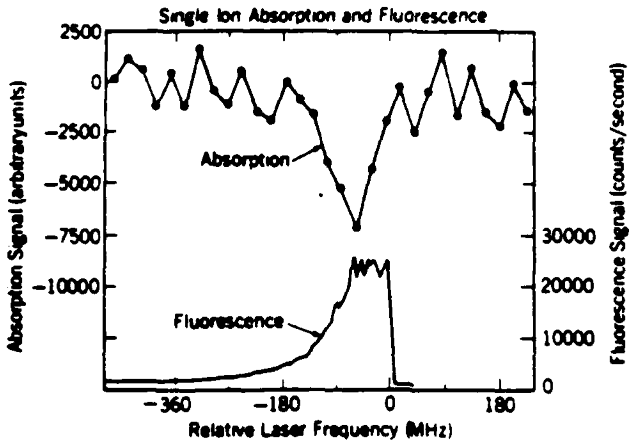

Fig. 9. Absorption signal observed as the 194 nm source is tuned through ν_0. Lower trace shows the simultaneously observed fluorescence scattering; the flat-topped appearance of this curve is due to the frequency modulation of the ion resonance. Integration times per point are 50 s and 10 s in upper and lower traces respectively.

4. <u>Quantum Jump Spectroscopy</u>. In the Hg^+ single ion experiment, when the 194 nm intensity approaches saturation level, then the ion is observed to decay from the $^2P_{½}$ level to the $^2D_{3/2}$ as indicated in Fig. 10. Once in the $^2D_{3/2}$ level the ion can either decay to the $^2D_{5/2}$ level or the ground ($^2S_{½}$) state. When the ion is in either D state, the 194 nm fluorescence ceases. This gives rise to a different quantum jump signature; in this case the off state corresponds to the ion being in either the $^2D_{3/2}$ or $^2D_{5/2}$ level.

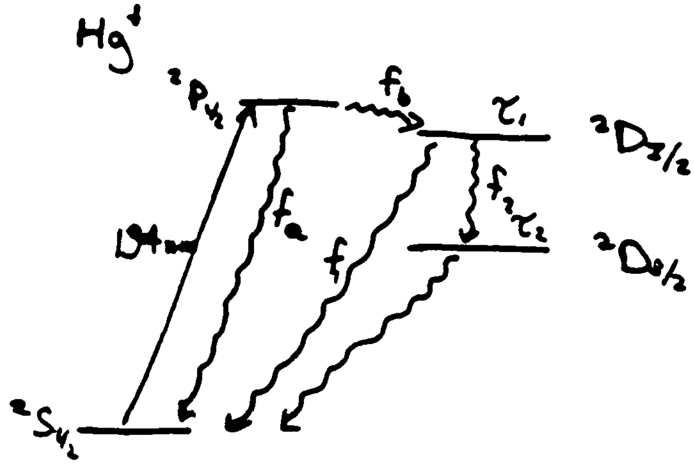

Fig. 10 Cascade process in Hg^+ ions indicated schematically in upper part of Figure. Quantum jumps due to this cascade process as observed in the bistable 194 nm fluorescence. Integration time per point is 1 ms.

Normally, if one desired to measure the lifetimes of the D states in Hg^+ or a similar system, one would detect the radiation corresponding to the S-D energy separation. Somewhat surprising here, is that we can measure both D state lifetimes <u>and</u> the branching ratios by analyzing only the statistics of the quantum jumps. In particular, by observing the distribution of "off" times for the 194 nm fluorescence, it is possible to determine f_1, f_2, f_a, f_b, $\tau(^2D_{3/2})$ and $\tau(^2D_{5/2})$. This can be done independent of the 194 nm intensity or tuning. Work is currently under way to make these measurements; statistical errors are at about the 5% level.

5. <u>Penning Trap/Superconducting Magnet System Made Operational</u>. This trap, whose cross-section is shown schematically in Fig. 11, has been installed in a superconducting magnet and initial tests performed on $^9Be^+$ samples:

(a) Densities of ~ $5 \times 10^7/cm^3$ observed. This is still at least an order of magnitude away from the Brillouin limit, indicating axial asymmetry in the trapping fields. By design, this trap should have very high axial electric symmetry but magnetic field/electric field alignment must still be performed.

(b) Field dependent nuclear spin flip transitions observed. Here, linewidths less than 0.1 Hz have been obtained while in previous traps using electromagnets, corresponding linewidths were at least 10 Hz wide. This appears to be primarily due to the increased magnet stability and should have profound consequences for spectroscopy.

(c) First images of ion "clouds" (nonneutral ion plasmas) have been made with a photon counting imaging tube. These images which can be observed in real time will greatly simplify and expand our plasma distribution function measurement ability.

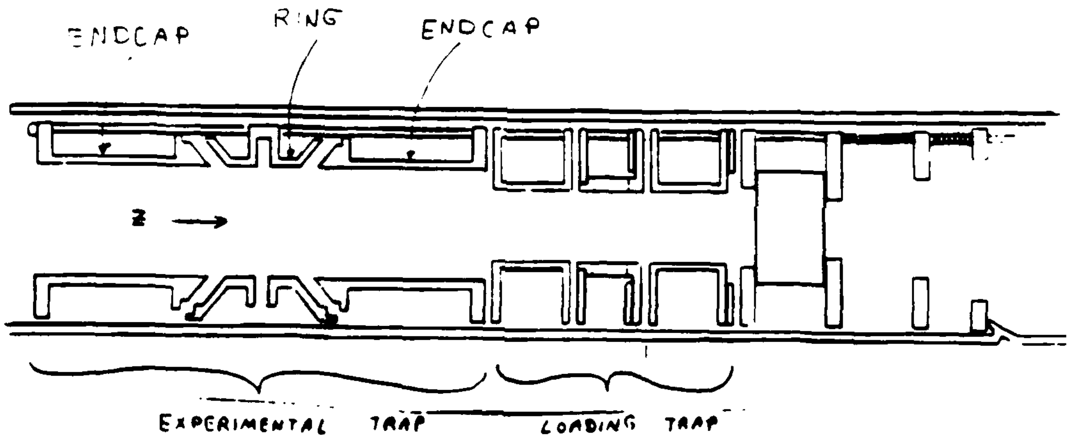

Fig. 11 New trap for superconducting magnet (for $^{26}Mg^+$, $^{25}Mg^+$, and $^{9}Be^+$ ions). The structure on the right is a second trap--for loading only.

6. Static Properties of Ion Plasmas. The primary limitation to high accuracy in spectroscopy of stored ions is the uncertainty in the second order Doppler shift. Therefore, it is critically important that we accurately determine the distribution functions for the trapped ions, in particular, the velocity distribution functions. In order to simplify these measurements in the future, we have carefully measured some of the static properties of these ion plasmas:

(a) Plasma Shear Measurements. For our single species ion plasmas, we are usually in the regime where the Debye length of the plasma is small compared to its dimensions; in this case, for ions in thermal equilibrium, we expect a "cloud" of constant density and no shear in the rotation velocity. (If there is shear, frictional heating would occur which would tend to drive the cloud to thermal equilibrium). We can search for shear by measuring the rotational velocity induced first order Doppler shift of an optical transition as a function of laser beam position perpendicular to the rotation (B field) axis. This is shown in Figure 12; to the extent that the slope of the plot is a straight line, there is no shear in the cloud. To within measurement precision, this is the case. This has now been verified on 3 separate experiments.

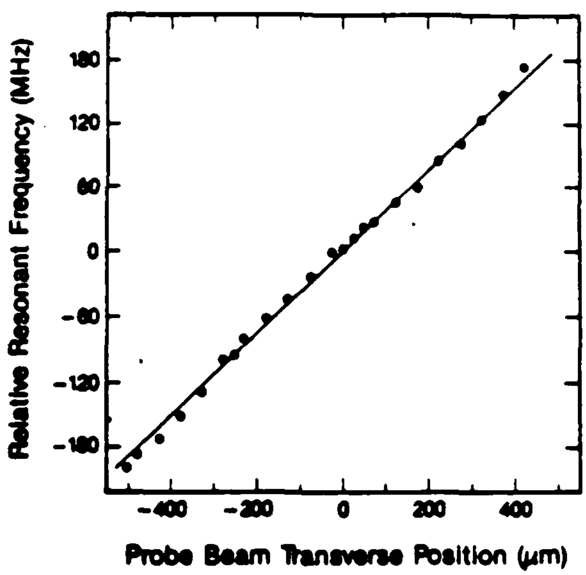

Fig. 12 Measured optical resonance frequency in Be^+ as a function of the transverse position (perpendicular to the trap axis) of the probe laser beam. These measurements placed a limit on the amount of shear in the Be^+ cloud. The statistical error in the data points is smaller than the size of the points.

(b) Plasma shape measurements. An additional result of our theory would indicate that the ion clouds are uniformly charged spheroids of

revolution (about the z or B field axis) and that there is a definite relationship between the aspect ratio of the plasma and the rotation frequency, independent of how the ion cloud is formed (by laser cooling). In the last year we have verified these relationships for 3 different experimental set-ups, and the results of this universal scaling are shown in Fig. 13.

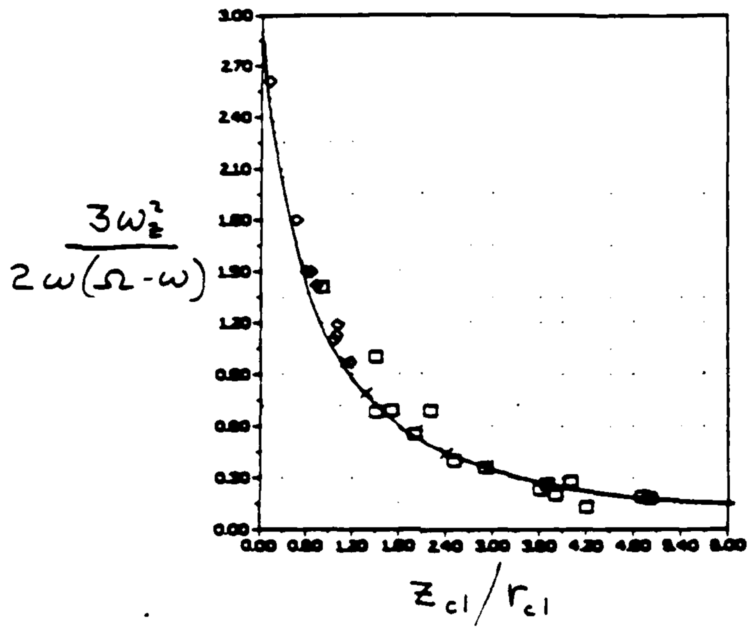

Fig. 13 Aspect ratio of ion plasmas vs. measured frequency parameter. ω_z is the single ion (center of mass) axial oscillation frequency, Ω is the cyclotron frequency and ω is the plasma rotation frequency. z_c /r_c is the ratio of spheroidal plasma axial extent to the diameter. The solid curve is a theoretical prediction.

7. <u>Synchrotron frequency divider</u>. If we are successful in the development of an optical frequency standard, its use will be somewhat limited since at present, devices do not exist to measure these frequencies in a phase coherent way, ie; count cycles of the radiation. The techniques of harmonic mixing (originally developed in the low frequency region) appear technically feasible but so far have not been applied to the visible spectrum. Moreover, such schemes are very cumbersome due to the many

lasers and mixing stages required. Additionally, the tuning range is limited.

The synchrotron divider (outlined in FY '87 proposal) could potentially overcome these difficulties. Aside from its possible practical applications, many interesting basic phenonema could be studied including the relativistic anharmonic oscillator, and extreme nonlinear interactions in a new regime. Presently, we are studying some of the basic processes involved. A graduate student is assembling apparatus necessary to make initial tests in the microwave region. Trap electrodes are nearly complete and superconducting magnet tests are underway.

8. Theory For all of the above experiments, the corresponding theory has been done. In addition, other theoretical topics have been addressed in the last year.

(1) Laser cooing limits. We have concentrated on the cooling limits for single ions. In particular, the limitations to the achievement of low kinetic energies for laser cooling of single ions confined in electromagnetic traps was studied. Sideband cooling of an ion in an rf (Paul) trap was re-examined including the effects of finite laser bandwidth and the effects of rf micromotion. Sideband cooling of ions in a Penning trap was examined for the first time. In both cases, cooling to the zero point energy of the ion in the trap should be possible and a method for verifying this condition was investigated. This report will appear in Phys. Rev. A.

(b) For the Mg^+ system discussed in part 1 above, the six level scheme of Fig. 5, was analyzed in detail including all coherences. We find that the mean ratio of the ground state level populations is 16 in the low intensity limit and for zero detuning. This ratio, unlike for the three level "V" configuration, is largely independent of laser intensity and is only weakly dependent on detuning. Somewhat surprising is that this ratio is independent of saturation and power broadening effects. As the laser intensity is increased

from zero, level 1 population decreases as population is transferred to level 3. One might expect, therefore, that the probability of transferring population from level 1 into the shelving level should diminish. However no such saturation effect is observed. The apparent explanation of this phenomenon is that population is transferred from level 3 to level 5 by the Raman coherence ρ_{35}. The increase in ρ_{35} with increasing Ω exactly compensates for the effect of the decreasing population in level 1. This work has been submitted to Phys. Rev. A.

(c) Ion trapping with large storage capacity has been investigated. The impetus of this work was efficient antimatter storage, but some of the results of this work will affect our experiments directly. (Conference proceeding)

(d) Negative resistance cooling has been investigated. The motivation for this study was the synchrotron divider, but it will have more general applicability. This work will be submitted to J. Appl. Phys.

OFFICE OF NAVAL RESEARCH

PUBLICATIONS† / PATENTS / PRESENTATIONS / HONORS REPORT

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"COOLED ION FREQUENCY STANDARD"

Principal Investigator

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PAPERS PUBLISHED IN REFEREED JOURNALS

1. "Sympathetic Cooling of Trapped Ions: A Laser-Cooled Two-species Nonneutral Ion Plasma," D.J. Larson, J.C. Bergquist, J.J. Bollinger, Wayne M. Itano, and D.J. Wineland, Phys. Rev. Lett. 57, 70 (1986).
2. "Observation of Quantum Jumps in a single Atom," J.C. Bergquist, R.G. Hulet, Wayne M. Itano, and D.J. Wineland, Phys. Rev. Lett. 57, 1699 (1986).
3. "Simple Electrodes for Quadrupole Ion Traps," E.C. Beaty, J. Appl. Phys. 61, 2118 (1987).
4. "Absorption Spectroscopy at the Limit: Detection of a Single Atom," D.J. Wineland, W.M. Itano, and J.C. Bergquist, Opt. Letters 12, 389 (1987).
5. "Laser Cooling," D.J. Wineland and W.M. Itano, Physics Today, vol. 40, no. 6, June, 1987. p. 34.
6. "Recoilless Optical Absorption and Doppler Sidebands of a Single Trapped Ion," J.C. Bergquist, W.M. Itano, and D.J. Wineland, Phys. Rev. A36, 428 (1987).

PAPERS SUBMITTED TO REFEREED JOURNALS

(not yet published)

1. "Laser spectroscopy of Trapped Atomic Ions," W.M. Itano, J.C. Bergquist, and D.J. Wineland accepted for Science magazine.
2. "Laser Cooling Limits and Single Ion Spectroscopy," D.J. Wineland, W.M. Itano, J.C. Bergquist and R.G Hulet, accepted for Phys. Rev. A.
3. "Quantum Jumps via Spontaneous Raman Scattering," R.G. Hulet and D.J. Wineland, accepted for Phys. Rev. A.
4. "Static Properties of a Nonneutral $^{9}Be^{+}$ Ion Plasmas," L.R. Brewer, J.D. Prestage, J.J. Bollinger, W.M. Itano, D.J. Larson, and D.J. Wineland, submitted to Phys. Rev. A.
5. "Observation of Quantum Jumps via Spontaneous Raman Scattering," R.G. Hulet, J.C. Bergquist, W.M. Itano, and D.J. Wineland, submitted to Phys. Rev. A.
6. "Measurement of HgII lifetimes and branching ratios via Quantum Jump Spectroscopy," W.M. Itano, J.C. Bergquist, R.G. Hulet, and D.J. Wineland, submitted to Phys. Rev. A.

BOOKS (AND SECTIONS THEREOF) PUBLISHED

1. "A High Γ, Strongly-Coupled, Nonneutral Ion Plasma," L.R. Brewer, J.D. Prestage, J.J. Bollinger, and D.J. Wineland, in Strongly Coupled Plasma Physics, edited by F.J. Rogers and H.E. Dewitt, Plenum press, 1986.

BOOKS (AND SECTIONS THEREOF) SUBMITTED

1. "Ion Traps for Large Storage Capacity," D.J. Wineland, Proc. of the "Cooling, Condensation, and Storage of Hydrogen Cluster Ions Workshop," SRI International, Menlo Park, CA. Jan. 8, 9, 1987.
2. "Observation of Quantum Jumps in Hg^+", W.M. Itano, J.C. Bergquist, R.G. Hulet and D.J. Wineland, for Proc. 8th Int. Conf. on Laser Spectroscopy, Sweden, June, 1987.

PATENTS FILED

None

PATENTS GRANTED

None

INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. "Fundamental Limits to Spectroscopic Accuracy," presented at the workshop on "Fundamental Measurements on Optically Prepared Atoms" NBS, Gaithersburg, MD, Sept. 29-30, 1986; D.J. Wineland.
2. "Single Atom Spectroscopy," presented at the Int. Conf. on Quant. Electronics, Apr. '87; J.C. Bergquist.
3. "Single Ion Spectroscopy," New York APS Meeting, March, '87; D.J.Wineland.
4. "Spectroscopy of Single Atoms," Boston DAMOP (APS) Annual Meeting, May, '87; D.J. Wineland.
5. "Ion Traps for Large Storage Capacity," Workshop on Cooling, Condensation, and Storage of Hydrogen Cluster Ions Workshop, SRI, Jan. '87; D.J. Wineland.
6. "Liquid and Solid Plasmas," Gordon Conf. on Atomic Physics, July '87; J.J. Bollinger.
7. "Precision Spectroscopy Using Trapped Ions," Symposium on the Physics of Stored and Trapped Particles, Sweden, June, '87; W.M. Itano.
8. "Cooling Limits in Traps," Symposium on the Physics of Stored and Trapped Particles, Sweden, June. '87; D.J. Wineland.
9. "The Observation of Quantum Jumps in Hg^+," 8th Int. Conf. on Laser Spectroscopy, Sweden, June, 1987; W.M. Itano.
10. "Strongly Coupled Nonneutral Ion Plasmas," 1987 Conf. on Atomic Processes in Plasmas, Santa Fe, NM, Sept. '87; J.J. Bollinger.
11. "Sympathetic Cooling of Positrons by Atomic Ions," Intense Positrons Beam Workshop, Idaho Falls, June '87; J.J. Bollinger.

OTHER INVITED TALKS

1. Colloquium, Colorado State University, Oct., '86; D.J. Wineland
2. Optical Phys. Technical Workshop, ILS, Seattle, Oct., '86' D.J. Wineland
3. Colloquium, U. of Virginia, Dec., '86; D.J. Wineland
4. Colloquium, U. of Colorado, Apr., '87; J.C. Bergquist
5. Colloquium, Cornell Univ., Apr., '87; D.J. Wineland
6. Colloquium, Rice Univ., March, '87, R.G. Hulet
7. Colloquium, Yale Univ., March, '87, R.G. Hulet
8. Seminar, Bell Labs, Murray Hill, Apr. '87; D.J. Wineland
9. Colloquium, Univ. of Missouri, Rolla, Sept '87; D.J. Wineland

HONORS/AWARDS/PRIZES

1. Election to Fellow, American Physical Society; D.J. Wineland

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